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**Direct Solar Pumping of Semiconductor Lasers:  
A Feasibility Study**

A semi-annual progress report to:

**The National Aeronautics and Space Administration**

Langley Research Center

for the period

June 1, 1990 - March 1, 1991

by:

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(NASA-CR-192184) DIRECT SOLAR  
PUMPING OF SEMICONDUCTOR LASERS: A  
FEASIBILITY STUDY Semiannual  
Progress Report, 1 Jun. 1990 - 1  
Mar. 1991 (Massachusetts Univ.)  
5 p

N93-19952

Unclass

G3/36 0145814

The primary goals of NASA Grant NAG-1-1148, entitled *Direct Solar Pumping of Semiconductor Lasers: A Feasibility Study*, are (i) to provide a preliminary assessment of the feasibility of pumping semiconductor lasers in space directly focused sunlight and (ii) to identify semiconductor laser structures expected to operate at the lowest possible focusing intensities. It should be emphasized that the structures under consideration would provide direct optical-to-optical conversion of sunlight into laser light in a single crystal, in contrast to a configuration consisting of a solar cell or battery electrically pumping a current injection laser. With external modulation, such lasers may prove to be efficient sources for intersatellite communications. We proposed to develop a theoretical model of semiconductor quantum-well lasers photopumped by a broadband source, test it against existing experimental data where possible, and apply it to estimating solar pumping requirements and identifying optimum structures for operation at low pump intensities. This report outlines our progress toward these goals. Discussion of several technical details are left to the attached summary abstract, which has been accepted for presentation on July 24 at the *IEEE Summer Topical Meeting on Spaceborne Photonics* in Newport Beach, California.

We have completed the basic laser model, which treats the most simple type of separate-confinement quantum-well-heterostructure (SCQWH) lasers. This type of laser was chosen since it provides for very low threshold operation. In its current form, the model treats rectangular-barrier single-well structures, such as that depicted in the figure appearing in the attached abstract. Our initial runs focused on structures of this type fabricated from the well established and commonly used AlGaAs-GaAs semiconductor system, even though this system is not expected to be the best choice for solar-pumped lasers. We first tested the model, suitably modified to treat injection lasers, against recent data for single-well AlGaAs-GaAs SCQWH laser diodes (*J. Appl. Phys.* **68**, 1964 (1990)). Absolute values for threshold currents were predicted to within a factor of about 1.3, and the predicted structure dependence of threshold current agreed well with experiment as well. Application of the model to the preliminary determination of pumping requirements and optimum structure identification was then undertaken. Optimization runs, carried out with user input since the optimization routine is not yet completed, indicated that structures consisting of a 55Å GaAs quantum well, 0.18µm Al<sub>0.32</sub>Ga<sub>0.68</sub>As waveguide layers, and 0.90µm Al<sub>0.70</sub>Ga<sub>0.30</sub>As cladding layers would operate at solar magnifications of 9300 suns (AM0). While slight reductions in the pumping requirements may result from structure modifications, we fully expect that the use of lower-band-gap materials will be required to significantly reduce lasing thresholds. Indeed, our model predicts a lasing threshold of <5000 suns for a Al<sub>0.70</sub>Ga<sub>0.30</sub>As-Al<sub>0.20</sub>Ga<sub>0.80</sub>As-In<sub>0.20</sub>Ga<sub>0.80</sub>As SCQWH laser of the same dimensions as the structure described above. This structure was chosen

somewhat arbitrarily, and with no attempts at optimization, indicating that large threshold reductions should be achievable by taking advantage of the superior lasing properties of strained-layer InGaAs quantum wells and the reduction of waveguide layer band-gaps (thus increased sunlight absorption) allowed by the use of these lower gap wells. (The lowest-threshold injection lasers currently existing are also based on InGaAs quantum wells.) We expect predicted pumping requirements for optimum structures with InGaAs quantum wells to be of the order of a few thousand suns, and will concentrate on such structures in our future studies.

The above discussion and the attached abstract describe the status of the project around the beginning of April, slightly beyond the end date of this belated report. Since then, graduate student Sreenath Unnikrishnan has presented his M.S. thesis proposal based on this work and received formal approval from his thesis committee. Work currently in progress and/or to be completed within the remaining few months includes extension of the model to treat graded-index waveguide layers and perhaps multiple wells, completion of the automated optimization routine, further investigation of trade-offs, identification of optimum structures in both of the above-mentioned material systems and perhaps others, sensitivity analyses, and preliminary studies of efficiency considerations. At the conclusion of our feasibility study, we plan to prepare and submit an article describing our study and optimum laser designs to an appropriate journal such as the *IEEE Journal of Quantum Electronics*.

# AlGaAs-GaAs Quantum-Well Lasers for Direct Solar Photopumping

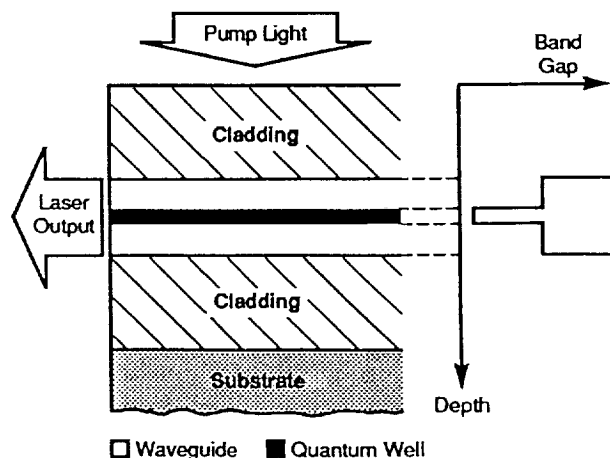
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Semiconductor lasers are well suited for space applications because of their small size, light weight, and low power consumption. Solar powering of spaceborne current injection lasers is possible using photovoltaic cells, but the efficiency of such a configuration may be limited by optical-to-electrical and electrical-to-optical energy conversion losses at the cell and laser, respectively. We are investigating an alternative solar pumping scheme in which a semiconductor laser would be *directly* photoexcited by focused sunlight. As part of a more comprehensive feasibility study of direct solar pumped semiconductor lasers, we have first considered lasers fabricated from the most common laser materials: AlGaAs and GaAs. Output from such lasers could be used directly, and would also be at wavelengths suitable for efficient pumping of Nd:YAG lasers.

We have specifically considered separate-confinement quantum-well-heterostructure (SCQWH) lasers since these lasers operate at low threshold excitation levels, and limited power is available in the usable portion of the solar spectrum. The SCQWH geometry we have examined is shown schematically below. This structure consists of high-gap  $\text{Al}_y\text{Ga}_{1-y}\text{As}$  cladding layers surrounding a medium-gap  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  waveguide (or optical confinement) region, the center of which is punctuated by a single GaAs quantum well layer. Unique design considerations arise for such a structure when solar photoexcitation is considered, as compositions and thicknesses which would yield minimum threshold operation in a diode structure can not be expected to minimize photoexcitation power requirements for solar pumping. For example, high-composition cladding regions and thin waveguide regions increase optical confinement, thus lowering threshold currents in injection lasers. In a solar pumped laser, however, absorption of sunlight would be maximized both by decreasing cladding layer compositions (thus band gaps) and increasing waveguide thicknesses. Hence, a trade off exists between absorption and optical confinement. In order to investigate this and other trade offs and to identify structures suitable for direct solar pumping, we have developed a model of SCQWH lasers which explicitly treats the case of photoexcitation by a broadband source.

Our model combines a straightforward treatment of gain and loss in the laser active region with explicit treatment of position- and wavelength-dependent light absorption and carrier transport through the structure. The gain spectrum of the quantum well is calculated assuming parabolic energy bands and a lineshape function which reflects both homogeneous and inhomogeneous broadening contributions. In calculating the gain and other properties, quasi-fermi levels are assumed constant throughout the waveguide region (including quantum well) and this



region is assumed to be charge neutral. Optical loss mechanisms include free-carrier absorption and a uniformly distributed scattering loss (assumed  $5\text{cm}^{-1}$ ) in addition to mirror losses. A standard dielectric slab model is used to treat optical confinement in the active region. Absorption of sunlight is treated using experimentally determined wavelength-dependent absorption coefficients and a 5800K blackbody approximation to the solar spectrum normalized to a total AM0 power density of  $137\text{mW/cm}^2$ . Transport of carriers to the active region from the top cladding layer, where photogeneration may be significant, is treated using a one-dimensional drift-diffusion model and typical values for recombination lifetimes and surface recombination velocity at the semiconductor/air interface. The waveguide region is assumed to collect all carriers incident on it from the cladding region, and the well is assumed to collect all carriers which enter or are generated within the waveguide region. Non-radiative recombination involving indirect conduction-band minima and Auger recombination are also considered. Cavity lengths of  $800\mu\text{m}$  are assumed for our calculations. Suitably modified and applied to broad-area AlGaAs-GaAs SCQWH injection lasers of similar cavity lengths, this model overestimates recently measured threshold currents (*J. Appl. Phys.* 68, 1964 (1990)) by a factor of  $\sim 1.3$  with no parameter adjustment. Absolute errors in prediction of thresholds, while very modest here, should not obscure identification of optimum structures as trends are more accurately predicted than absolute threshold currents.

In our initial investigations of the feasibility of direct solar pumping of these lasers, we have used our model to identify structures which operate at the lowest solar photoexcitation levels. While we have not yet rigorously identified an optimum structure, lowest thresholds seem to occur for lasers with  $\sim 55\text{\AA}$  quantum wells,  $\sim 0.18\mu\text{m}$  waveguide layers with compositions near  $x \sim 0.32$ , and  $\sim 0.9\mu\text{m}$  cladding layers with compositions near  $y \sim 0.70$ . Significantly thinner wells and lower composition waveguide layers increase thresholds by reducing carrier confinement in the quantum well. Significantly thicker confining layers increase thresholds by increasing the number of carriers photogenerated in the top confining layer which are lost to recombination before diffusing to the waveguide and well. Cladding-layer composition and waveguide thickness roughly trade off, with increases in one allowing increases in the other for a given threshold magnification. For a structure using the parameters listed above (identically), our model predicts a solar threshold required for lasing of 9300 suns. Further reduction should be possible using a multiple-quantum-well active region and/or graded-gap waveguide layers, but lower bounds will be set by the minimum band gaps practical for the materials used. Use of lower gap materials can be expected to significantly reduce solar pumping requirements, even though reductions from enhanced absorption will be opposed by increasing Auger losses in some cases. Indeed, initial results for strained-layer  $\text{Al}_{0.70}\text{Ga}_{0.30}\text{As}-\text{Al}_{0.20}\text{Ga}_{0.80}\text{As}-\text{In}_{0.20}\text{Ga}_{0.80}\text{As}$  SCQWH lasers with structural dimensions identical to those described above suggest that laser operation should be possible at solar photoexcitation levels of  $< 5000$  suns for such a structure.

To summarize, we have theoretically examined the solar power requirements for low-threshold AlGaAs-GaAs quantum-well lasers *directly* photopumped by focused sunlight. Using a laser model which explicitly treats absorption and transport phenomena relevant to solar pumping, and which yields threshold current predictions for injection lasers, we have identified separate-confinement single-quantum-well laser structures which should operate at photoexcitation intensities of less than 10000 suns. We expect that further optimization of structural parameters, modification of structural configuration, and use of lower-gap semiconductors will reduce pumping requirements to less than 3000 suns. Reduction of pumping requirements will be a focus of our future studies, and optical-to-optical power efficiencies for optimum structures will be compared with those expected from injection lasers driven by photovoltaic cells.

*This work is supported by NASA (Grant NAG-1-1148).*